

A Population Explosion: The Nature and Evolution of X-ray Binaries in Diverse Environments  
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## An Overview of the Bowen Survey; detecting donor star signatures in Low Mass X-ray Binaries

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**Abstract.** In this paper we give a review of the Bowen fluorescence survey, showing that narrow emission lines (mainly N III and C III lines between 4630 and 4660 Å) appear to be universally present in the Bowen blend of optically bright low mass X-ray binaries. These narrow lines are attributed to reprocessing in the companion star giving the first estimates of  $K_2$ , and thereby providing the first constraints on their system parameters. We will give an overview of the constraints on the masses of the compact objects and briefly highlight the most important results of the survey. Furthermore, we will point out the most promising systems for future follow-up studies and indicate how we think their estimates of the component masses can be improved.

### 1. Introduction

One of the main aims of optical observations of low-mass X-ray binaries (LMXBs) has always been to find a signature of the donor star, and thereby constrain the masses of both components. Unfortunately, the optical emission of most LMXBs that accrete at high rates is completely dominated by the reprocessing of the X-rays in the outer accretion disk. This is the reason why, in spite of optical counterparts being known for persistent LMXBs for years

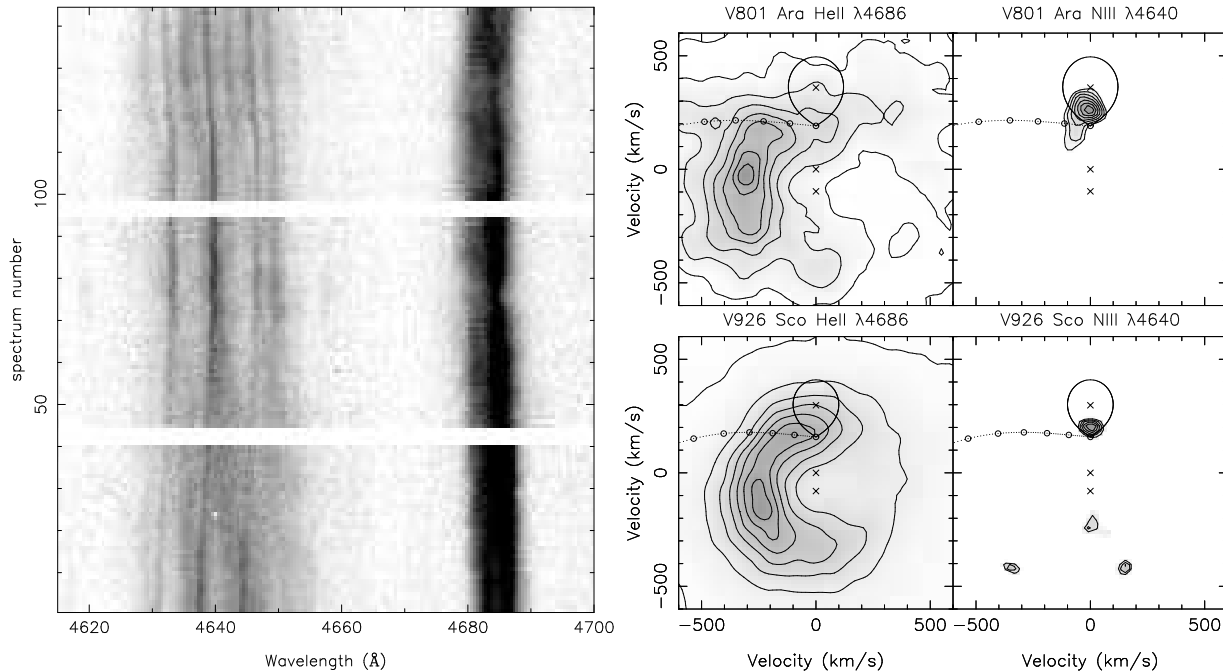


Figure 1. *Left:* Triled spectrogram of the Bowen blend and He II  $\lambda 4686$  of Sco X-1 showing the presence and the movement of the narrow emission lines. From Steeghs & Casares (2002). *Right:* Example Doppler maps of He II  $\lambda 4686$  (left) and the Bowen region (right) for 4U 1636–536 (top) and 4U 1735–44 (bottom). The He II maps trace the accretion disk, while the Bowen maps are dominated by a compact spot at the phasing and velocity where the companion star is expected. The Roche lobe of the secondary and the gas stream trajectory are overplotted for clarity. From Casares et al. (2006).

(sometimes even over 20 years), no strong constraints on their system parameters existed until recently.

The discovery of narrow high-excitation emission lines in the bright LMXB Sco X-1 opened new opportunities for system parameter constraints in active X-ray binaries (Steeghs & Casares 2002). Phase-resolved blue spectroscopy showed that these narrow lines moved in anti-phase with the compact object, strongly suggesting that they arise from the irradiated surface of the donor star. This led to the first estimate of the semi-amplitude of the radial velocity of the secondary,  $K_2$ , and mass function ( $f(M_1) = K_2^3 P_{\text{orb}} / 4\pi G$ ) of Sco X-1. These lines were most prominent in the Bowen region (the region from 4630 to 4660 Å), that mainly consists of a blend of N III and C III lines. The N III lines are the result of a UV fluorescence process, while the C III lines are due to photo-ionization and subsequent recombination (McClintock et al. 1975). In this paper we review the results of a survey we performed to apply this new technique to other persistent LMXBs or transients during outburst in order to find a donor star signature.

## 2. The observed sources

After the detection of the narrow emission lines in the Bowen region in Sco X-1 (see Fig. 1/Left), a systematic survey was performed targetting active LMXBs with known optical counterparts brighter than  $V \simeq 20$ . Thus far, phase resolved spectroscopy has been performed for 7

Table 1. Overview of all LMXBs that we have studied thus far. Indicated are the compact object mass limits, derived from the narrow Bowen features, for each source. The transient sources in our sample are indicated with an asterisk (\*).

Source	Mass limits ( $M_{\odot}$ )	reference
Sco X-1	$\geq 0.05$	Steeghs & Casares (2002)
GX 339-4*	$\geq 5.8$	Hynes et al. (2003)
X1822-371	$\geq 1.61$	Casares et al. (2003) Muñoz et al. (2005)
4U 1636-536	$\geq 0.76 \pm 0.47$	Casares et al. (2006)
4U 1735-444	$\geq 0.53 \pm 0.44$	Casares et al. (2006)
Aql X-1*	$\geq 1.2$	Cornelisse et al. (2007a)
4U 1254-69	1.20-2.64	Barnes et al. (2007)
GX 9+9	$\geq 0.22$	Cornelisse et al. (2007b)
LMC X-2	$\geq 0.86$	Cornelisse et al. (2007c)

persistent and 2 transient LMXBs, using either the WHT, AAT, NTT or VLT telescope. In all cases a signature of the donor star was detected, leading to a first estimate of their mass functions. We have listed the observed sources plus the mass constraints of their compact objects in Table 1.

For most systems the narrow emission lines are too faint to be detectable in the individual spectra. Fortunately, thanks to the technique of Doppler tomography it is possible to use the information contained in all phase resolved spectra at once to reconstruct the emission distribution of the Bowen emission lines in velocity space. In all cases this produced a compact spot consistent with the phasing and the velocity of the companion star (for an example see Fig. 1/Right).

Apart from the problems that are inherent to all other methods to estimate the system parameters of LMXBs (such as not knowing the inclination or the radial velocity semi-amplitude of the primary,  $K_1$ , for most sources), the Bowen technique has another disadvantage. The velocity determined from the narrow components is only a lower-limit to the true  $K_2$  velocity, since these lines arise on the irradiated side of the donor star which (for most of the systems) does not correspond to the center of mass of the secondary (note that this is also a problem for absorption lines if heating is significant). This displacement can be accounted for by the so-called  $K$ -correction, which depends on the inclination of the system, the opening-angle of the accretion disk, the mass ratio (see Muñoz et al. (2005)).

### 3. Highlights

Thus far, the survey has shown that all observed systems show narrow emission lines in the Bowen region that can be attributed to the irradiated surface of the companion. In Fig. 2 we show Bowen region of the average Doppler corrected spectra in the rest frame of the companion, and in all spectra narrow N III and/or C III lines are visible. This suggests that this technique can be universally applied, and is an excellent tool to constrain the system parameters of LMXBs. Not only does it appear to work for persistent sources, but GX 339-4 and Aql X-1 have shown that it can also work for transients during outburst. This technique can therefore also be used to constrain the system parameters for transients that are too faint in optical when they return to quiescence.

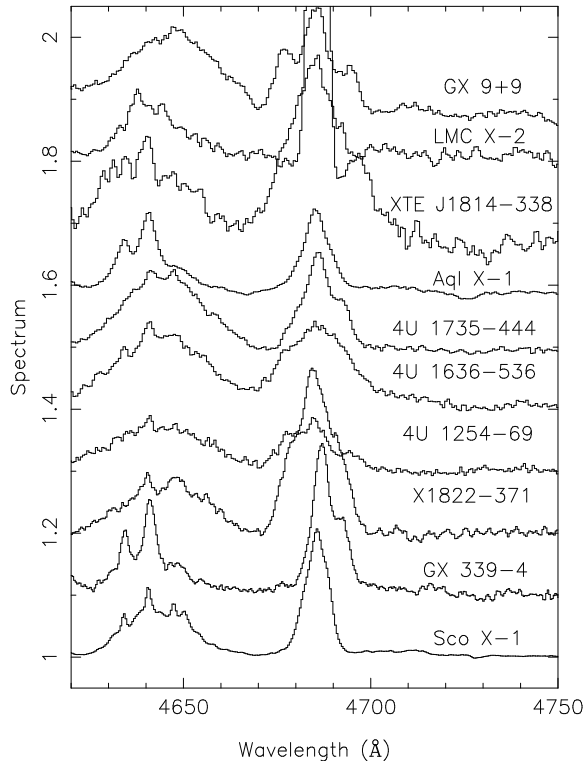


Figure 2. Average Doppler corrected spectra of the Bowen region in the rest frame of the companion. Shown are the systems observed by our group thus far.

The observation of GX 339–4 is a spectacular demonstration of the power of the Bowen fluorescence technique. Despite being one of the earliest proposed black hole candidates even its orbital period was uncertain due to the bright accretion disk that still dominates the optical flux when the system is in quiescence. This made it not possible to directly measure the system parameters of this system thus far. After applying the Bowen technique to GX 339–4 a mass function of  $5.8M_{\odot}$  was found, finally confirming the black hole nature of its compact object (Hynes et al. 2003).

Another interesting case is the neutron star transient Aql X-1. In quiescence the counterpart is 2 magnitudes fainter than a nearby star, severely hampering quiescent studies. During a 2004 outburst we had the opportunity to take several high resolution blue spectra, and the narrow emission components were clearly present in the individual spectra. The resulting radial velocity curve lead to a lower limit on the mass function of  $f(M_1) \geq 1.23 \pm 0.12 M_{\odot}$ . Combining this with estimates for the rotational broadening of these lines suggests that the mass of the compact object is  $\geq 1.6M_{\odot}$  (at 95%), strongly implying a massive neutron star in Aql X-1 (Cornelisse et al. 2007a).

Not only does this technique work for Galactic LMXBs, but it has also been successfully applied to the extra-galactic system LMC X-2 (Cornelisse et al. 2007c). From the He II  $\lambda 4686$  emission line it was possible to determine a spectroscopic period of  $0.32 \pm 0.02$  day, that was interpreted as the orbital period. However, the spectra do show a longer term variation that is most likely due to a precessing accretion disk. Despite these difficulties,

plus the fact that the Bowen emission is much weaker compared to the Galactic systems, it was possible to detect the narrow lines using Doppler tomography.

As already pointed out, a main problem in determining the system parameters from dynamical studies of LMXBs is the lack of knowledge of  $K_1$  and the inclination. However, for several systems these parameters are known, making them excellent system to derive strong constraints on the component masses. For 4U 1254–69 the inclination is well constrained due to the presence of dips, while  $K_1$  is known for the neutron star LMXB 4U 1636–53. However, the most promising system is the eclipsing pulsar X1822–371, for which both the inclination and  $K_1$  are known. By accurately modelling the narrow components for this system it should be possible to strongly constrain both the donor and neutron star mass (Muñoz-Darias et al. 2008 in prep.).

#### 4. Conclusions

We have given a short overview of the novel technique of Bowen fluorescence that has proven itself to work for the 9 systems thus far observed (see Table 1), and for most of the systems we have been able to derive the first constraints on their system parameters ever. There are still a handful of persistent LMXBs left that are bright enough for this technique, and there are plans to also observe these systems. Recently 4U 1957+11 has been observed with Magellan, and in the near future EXO 0748–676, Ser X-1 and 4U 1556–605 will be observed with the VLT. Furthermore, this technique might also be an excellent tool to determine the system parameters of future bright transients.

The next step will be to improve the determined  $K_2$  velocities for the most promising candidates by measuring the distribution of the emission across the Roche-lobe using high resolution spectroscopy. This will allow us to more accurately measure the radial velocities of the narrow lines, determine their rotational broadening, and hopefully model the shape of the lines as a function of orbital period in order to get a better constraint on the  $K$ -correction. Furthermore, we have started using the fact that the Bowen lines are efficiently reprocessed on the donor star to constrain the inclination and the  $K$ -correction using Echo-tomography with a narrow band filter centered around the Bowen blend (for more information see Muñoz-Darias et al. in this volume). These next steps will hopefully provide stronger constraints on the masses of LMXBs, and in particular give accurate neutron star masses.

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